
Aging and stem cell renewal

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Abstract

Adult or organ stem cells present in mammalian organ systems are essential for the maintenance and repair of these organs throughout adult life. This key function of adult stem cells requires precise coordination of highly regulated molecular signaling to ensure proper cellular, tissue, and organ homeostasis. Such coordination deteriorates with age and consequentially, adult stem cells in the aged organism do not regenerate tissue damaged by stress, injury or attrition as efficiently as in the young. The molecular mechanisms associated with deficits in organ stem cell function with advancing age are for the most part unknown. Nonetheless, recent studies are beginning to shed light on the processes involved in stem cell aging, particularly in adult skeletal muscle stem cells, namely satellite cells. In this chapter, the current mechanisms believed to contribute to stem cell aging are reviewed, focusing on satellite cells and comparing them to hematopoietic stem cells as these cell types offer interesting perspectives regarding extrinsic versus intrinsic aging programs. Undoubtedly, knowledge of how organ stem cells change with advancing age will help in understanding the aging process itself and might provide novel therapeutic venues for the enhancement of tissue regeneration.

1. Stem cell aging and loss of tissue regenerative potential

Mammalian organ systems are repaired and maintained by dedicated subsets of resident cells that are collectively called adult or organ stem cells as well as progenitor or precursor cells. For the sake of convenience, all such cells (including satellite cells) will be henceforth referred to as stem cells even though it may not be the case for all organs and tissues. Similarly to the embryonic stem cells that build organs, adult stem cells that regenerate organs are capable of symmetric and asymmetric divisions, self-renewal and differentiation. Coordinating these cell-fate decisions in adult tissues is critically important for the maintenance of cellular homeostasis and hence for organ function. This precise coordination of complex stem cell responses throughout adult life is regulated by evolutionary conserved signaling networks that cooperatively direct and control (1) the breakage of stem cell quiescence, (2) cell proliferation and self-renewal, (3) cell expansion and prevention of premature differentiation and finally, (4) the acquisition of

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the terminal cell fate. This highly regulated process of tissue regeneration recapitulates embryonic organogenesis with respect to the involvement of interactive signal transduction networks, such as Notch, Wnt, TGF- β , Shh and Ras/MAPK (Carlson et al., 2008; Wagers et al., 2005).

With advancing age the regenerative properties of organ stem cells deteriorate and the integration of the molecular signaling responsible for the productive responses of these cells becomes altered in ways that make tissue repair inefficient (Conboy et al., 2003; Molofsky et al., 2006; Rossi et al., 2007; Wagers et al., 2005). While the notion of an age-specific decline in regeneration has existed for a long time, the molecular and cellular determinants of this unfortunate outcome are not entirely understood and are a subject of active investigation. In recent years, the interconnected roles of the intrinsic and extrinsic/niche based factors in the aging of tissue regeneration have begun to emerge, not only improving our understanding of the aging process, but also suggesting potential therapies for the enhancement of tissue repair in the old. The following discussion of stem cell aging mechanisms will be restricted, for the most part, to studies on adult skeletal muscle and hematopoietic stem cells. This review is by no means exhaustive and only highlights the major aging mechanisms reported in the literature for these two stem cell types.

The regeneration of skeletal muscle is a perfect example of a tissue that relies on life-long maintenance by endogenous stem cells, called satellite cells (Hawke et al., 2001; Mauro, 1961; Muir et al., 1965; Wagers et al., 2005). With aging, the process of muscle regeneration by resident stem cells becomes inefficient, which leads to a replacement of functional muscle by fatty and fibrous tissue (Brack et al., 2007; Marshall et al., 1989). This age-related, acquired muscle atrophy known as sarcopenia is phenotypically similar to congenital myopathies, where satellite cells struggle to keep up with the constant death of genetically deficient muscle fibers (Grounds, 1998; Gruenbaum et al., 2005; Radley et al., 2007; Smith et al., 2005).

Additionally, sarcopenia is associated with altered microtubule networks leading to disordered distribution of nuclei in old myofibers, which might introduce transport limitations to some cell compartments (Bruusgaard et al., 2006). Abnormalities in the microtubules may stem from nonenzymatic glycosylation and other posttranslational modifications of microtubule-associated proteins due to alterations in protein metabolism in old muscles (Bruusgaard et al., 2006). Irregular and fragmented nuclei are also found in aged myofibers, thus indicating that apoptotic events possibly triggered by accumulated DNA damage in these fibers are responsible at least in part by the loss of nuclei and muscle mass in the old (Bruusgaard et al., 2006). Moreover, sarcopenia has also been correlated to anatomic or functionally deficient muscle innervation in elderly individuals and indeed old animals have slow or impaired muscle reinnervation capacity as compared to young (Carlson et al., 1989; Choi et al., 1996).

The outstanding regeneration abilities inherent in adult skeletal muscle can be attributed almost exclusively to the small satellite cell population resident in this tissue (Hawke et al., 2001; Wagers et al., 2005). Satellite cells are located in a niche under the basal lamina but outside of the muscle fiber sarcolemma (Hawke et al., 2001; Le Grand et al., 2007; Wagers et al., 2005). Satellite cells were first identified in electron microscopic studies of frog skeletal muscle fibers (Mauro, 1961). These cells were first described as being “wedged” between the muscle fiber sarcolemma and the basement membrane, and this intimate association was persistent along the length of the frog tibialis anticus muscle fibers (Mauro, 1961). Interestingly, electron micrograph observations revealed that the surface of the myofiber is distorted inwards, with its myofibrils being pushed aside to accommodate the satellite cell and it was conjectured that these newly identified “dormant myoblasts” were present in all vertebrate skeletal muscles (Hawke et al., 2001; Mauro, 1961).

Later, more detailed studies on muscles derived from fruit bats and white mice revealed that satellite cells are uniformly distributed and indeed osmotically independent from muscle fibers (Muir et al., 1965). In addition, these mononucleate fusiform satellite cells possess a high nuclear-to-cytoplasmic ratio, few organelles and increased nuclear heterochromatin as compared to myonuclei (Hawke et al., 2001; Muir et al., 1965). These satellite cell features are consistent with its relatively quiescent and transcriptionally less active nature (Hawke et al., 2001). Satellite cell density depends on the age, species and type of myofiber, constituting about 30% of muscle nuclei in the neonate but only 2-4% in adult mice (Hawke et al., 2001). There is no significant decline in the satellite cell numbers in mice and humans (Conboy et al., 2003; Roth et al., 2000; Wagers et al., 2005) and their proliferative potential is nearly constant since satellite cells isolated from both young (9-year-old) and old (≥ 60 -year-old) humans are capable of about 20 to 30 replications in vitro under standard growth conditions (Hawke et al., 2001; Renault et al., 2000). Also, mouse satellite cells isolated from young (3-6 mo), adult (7-10 and 11-13 mo), old (19-25 mo) and senile (29-33 mo) mice show the same proliferative capacity during short-term cultures in vitro, provided that the mitogenic milieu of older cells is properly enriched with FGF (Shefer et al., 2006). It has also been demonstrated that a minor subset of aged

mouse satellite cells (22-30 mo) is as capable of self-renewal and regeneration as young cells both in vitro and after myofiber engraftment into mdx-nude host mice (Collins et al., 2007).

Quiescent satellite cells are reported to express CD34 and Pax7, β 1-integrin and CXCR4, but are also known to be a heterogeneous population with possible differences in myogenic potential among stem cell sub-populations (Collins et al., 2007; Cossu et al., 2007; Mitchell et al., 2005; Sherwood et al., 2004; Wagers et al., 2005). The activated satellite cell progeny (i.e., fusion-competent myoblasts) also express Pax7, β 1-integrin and CXCR4, as well as desmin, Myf-5 and MyoD; and to this date, there is no known unique genetic marker of quiescent satellite cells and no clear understanding of how quiescence in these cells is established and maintained (Wagers et al., 2005). Another subset of myofiber-associated cells is CD45⁺ leukocytes that become numerous in the injured muscle due to the inflammatory response, but are not themselves myogenic (Polesskaya et al., 2003; Sherwood et al., 2004; Wagers et al., 2005). Very little is known about age-specific changes in the profile of muscle stem cells and potential differences in the genetic marker expression. Hence, sub-population composition is yet to be determined with respect to satellite cells residing in young versus aged muscle. Nonetheless, advances are being made in identifying potential genetic markers for the satellite cell subpopulations, which are most likely generated via asymmetric (perpendicular to the muscle fiber) and symmetric (along the myofiber axis) muscle stem cell divisions (Cossu et al., 2007).

In contrast to the in vitro observations discussed above (Hawke et al., 2001; Renault et al., 2000; Shefer et al., 2006), satellite cells in aged muscles display an impaired ability to activate and proliferate in response to injury and represents one of the key age-specific defects in muscle repair (Conboy et al., 2002; Conboy et al., 2003; Wagers et al., 2005). Activation of these quiescent cells for proliferation is triggered by injury or attrition of mature muscle fibers. By 24 hours after muscle injury, satellite cells enter the G1/S phase of the cell cycle and robustly proliferate for the next 2-3 days (Hawke et al., 2001). This expansion of muscle stem cells is accompanied by their differentiation along the myogenic lineage; first into a pre-myoblast subset that expresses high levels of Pax3 and then into fusion-competent myoblasts that are desmin^{hi}, pax7^{hi} and pax3^{lo/-} (Wagers et al., 2005). Myf-5 was also reported to be up-regulated early during satellite cell activation and then to be down-regulated in the fusion-competent myoblasts (Brack et al., 2008). During this stage of de novo adult myogenesis, satellite cell progeny undergoes asymmetric cell divisions with respect to cell-fate determination and with respect to the segregation of template DNA strands (Conboy et al., 2007).

The process of muscle regeneration culminates in the production of de novo multinucleated myofibers. In mice, it has been well established in recent literature using standard injury models (cardiotoxin or dry ice) and a variety of techniques such as histology, immunofluorescence staining, Western Blotting, FACS, and high-throughput microarray analysis that muscle regeneration shifts from myogenic cell proliferation to myoblast differentiation events at around day 3 post-injury (Hawke et al., 2001; Yan et al., 2003). In fact, the highest levels of myogenic cell proliferation and expression of regulators of cell cycle progression and DNA replication are observed at 3 days after injury (Yan et al., 2003). Newly generated myofibers with their characteristic centrally-located nuclei, expressing embryonic myosin heavy chain and resulting from the fusion of satellite cell progeny (i.e., myoblasts), typically do not appear in massive numbers until 4 to 5 days after muscle injury (Hawke et al., 2001; Yan et al., 2003). However, it is still possible to detect a few nascent myofibers at earlier time points post-injury (Yan et al., 2003), especially around the periphery of the injury site where muscle was less damaged. In mice, no significant age-specific defect in this terminal differentiation, i.e. fusion of myoblasts into myotubes, is observed (Conboy et al., 2003).

The process of myogenic differentiation was reported to be regulated by an antagonistic balance between active Notch and Wnt/ β -catenin signaling pathways (Brack et al., 2007; Brack et al., 2008; Conboy et al., 2002; Conboy et al., 2003). Specifically, active Notch allows cell proliferation and prevents premature differentiation by inhibiting Wnt signaling in muscle progenitor cells via the induction of GSK-3 β , which in turn promotes the degradation of β -catenin (Brack et al., 2008; Conboy et al., 2002). Later on, the Notch antagonist Numb is upregulated, which inhibits Notch activity and allows for the Wnt pathway to promote differentiation into myoblasts and myotubes (Brack et al., 2008; Conboy et al., 2002). Consequently, injections of exogenous Wnt3A into injured muscle at specific time points causes replacement of muscle with fibrous tissue because the expansion of myogenic progenitor cells terminates prematurely and thus not enough cells are available for regeneration, i.e. de novo myofiber production (Brack et al., 2007; Brack et al., 2008). This defect in muscle repair was also connected with a reported ability of Wnt to skew the myogenic cell fate of satellite cells into the fibroblast lineage (Brack et al., 2007). Thus, very interestingly, Wnt may both (1) promote myogenic lineage determination (Brack et al., 2008) and (2) inhibit myogenic cell fate (Brack et al., 2007), presumably, depending on the timing of Wnt signaling in the muscle niche.

The molecular regulatory mechanisms of cell fate decisions during regeneration of adult skeletal muscle are depicted in Figure 1.

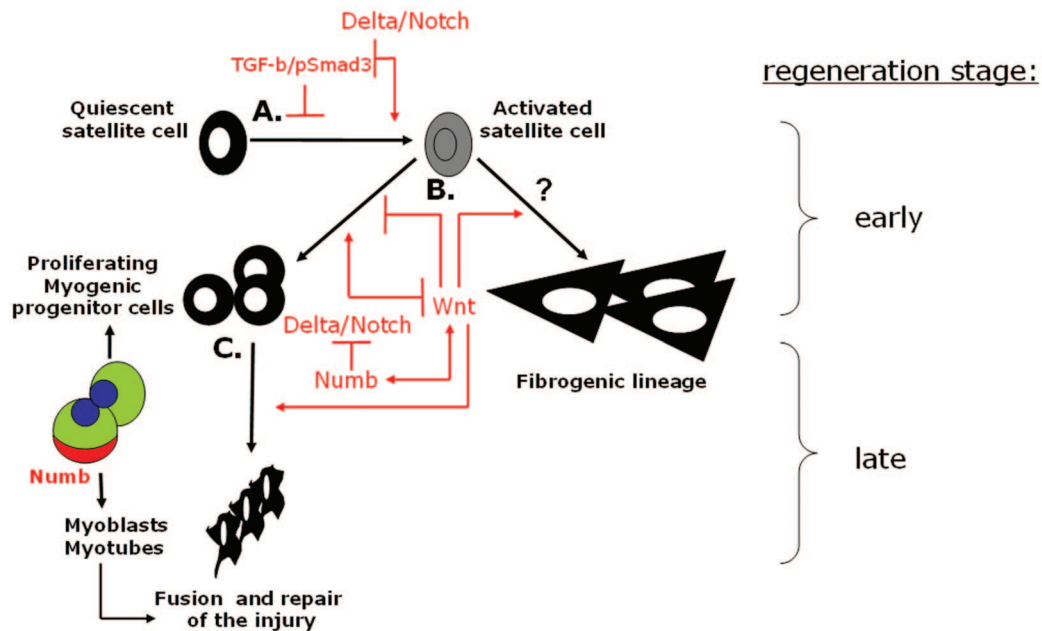


Figure 1. A model of signalling networks regulating myogenic cell-fate. **A.** Activation of quiescent satellite cells to proliferate is induced by the upregulation of Notch ligand, Delta, on the surface of myofibers located near the injury site and on the satellite cells themselves. TGF- β /pSmad3 antagonize this process by keeping high levels of CDK inhibitors in satellite cells and the age-specific increase in pSmad3 accompanied by the decline in active Notch thus precludes satellite cell activation. **B.** Activated myogenic progenitor cells (progeny of satellite cells) proliferate without differentiation due to high levels of active Notch that inhibits Wnt signalling pathway. Wnt signaling may also skew the myogenic cell fate of satellite cells towards the fibroblast lineage in the early phase of the regenerative response. **C.** In the late stages of regeneration, differentiation of myogenic progenitor cells into fusion-competent myoblasts is induced by the up-regulation of Numb that inhibits Notch activation and thus, Wnt signalling is released to promote terminal myogenic cell fate. A representative picture of a myogenic progenitor cell that divides asymmetrically with respect to the levels of Numb is also shown in the insert. Cells with high Numb will go on to give rise to myoblasts and myotubes that replace damaged muscle; cells with low Numb continue to divide as pre-myoblast myogenic progenitors. Numb and Wnt might also re-enforce each other.

2. Aging of stem cell niches and intrinsic aging of stem cells

Individual myofibers are surrounded by a dynamic, collagen-rich interstitial connective tissue known as endomysium, comprised of a diverse array of extracellular matrix (ECM) components (Grounds et al., 2005). Linkages between the basal lamina and the endomysium are mediated by different adhesive and structural molecules that form a complex interconnected mesh (Grounds et al., 2005). Collagen VI, for instance, functions as a bridge between the basement membrane and the interstitial ECM via its ability to bind a variety of molecules such as integrins, collagen I and II, decorin as well as many basal lamina components including collagen IV and perlecan (Grounds et al., 2005; Sanes, 1982). Myogenic laminins (e.g., laminin 2/4) are a major component of the myofiber basement membrane and they also interact with the collagen IV network and perlecan (Grounds et al., 2005; Sanes, 1982). Perlecans and syndecans belong to the family of heparan sulfate proteoglycans, which are crucial in mediating binding between muscle regeneration-associated growth factors (e.g., FGF-2 and HGF) and their receptors (Cornelison et al., 2001; Langsdorf et al., 2007; Wagers et al., 2005).

Aging is invariably associated with a reduction in the regenerative capacity of organ stem cells, eventually leading to the accumulation of unrepaired, damaged tissues in the old organism (Janzen et al., 2006; Molofsky et al., 2006; Wagers et al., 2005). To the extent that this decay in stem cell function with age is caused by intrinsic molecular alterations (e.g., oxidative damage and decreased mitochondrial function) or extrinsic changes in the stem cell microenvironment is not entirely understood (Molofsky et al., 2006; Wagers et al., 2005). Interestingly, multiple lines of evidence exist to substantiate both intrinsic and extrinsic factors as mediators of the negative age-related changes in stem cell function depending on the organ stem cell niche under consideration.

In terms of extrinsic stem cell aging mechanisms, reports on adult skeletal muscle regeneration offer the most compelling case and many intriguing perspectives. It is well known that extensor digitorum longus (EDL) muscle autografts generate greater mass and develop higher maximum contractile force in young than old rats (Carlson et al., 1989). Moreover, cross-age transplantation experiments showed that the regenerative ability of young and old muscle grafts depended solely on the age of the host as young hosts allowed successful engraftment of both young and old muscles while both graft types failed to regenerate in old rats (Carlson et al., 1989). Similar results were obtained in minced muscle auto- and heterotransplants in anterior tibial muscles in mice (Zacks et al., 1982). Therefore these transplantation studies established that the extrinsic factor(s) present in the old host environment significantly limit the intrinsic muscle regeneration capacity, especially in the context of late regeneration events such as reinnervation and ultimately functional properties.

However, the specific local and/or systemic extrinsic factor(s) responsible for poor muscle regeneration in old hosts and, more importantly, how these factors influenced early regeneration events like satellite cell activation and proliferation, were still largely unknown (Carlson et al., 1989). Some extrinsic factors suggested to play a role in successful muscle regeneration include proper reinnervation (as evidenced by abnormal neuromuscular junction patterns observed in grafts into old animals), revascularization, hormones, growth factors, and biomechanical aspects (Carlson et al., 1989). Nonetheless, early muscle regeneration events up until the fusion stage are considered independent of innervation status and thus age-associated muscle denervation effects most likely play a minor role in deficient muscle repair after injury (Grounds, 1998; Zacks et al., 1982).

It was also suggested that the age-related decline in muscle regeneration was associated with a concurrent fall in phagocytic macrophage clearance activity during the early stages of muscle repair in SJL/J mice (Zacks et al., 1982). Co-culturing muscle minces with bone marrow cells in diffusion chambers implanted in the peritoneal cavity of mice resulted in faster regeneration as compared to chambers with muscle alone or muscle mixed with gold-pretreated (which impairs phagocytic activity) bone marrow (Yarom et al., 1977; Zacks et al., 1982). Indeed, both macrophage infiltration and muscle regeneration events after injury are slower in old than in young rats (Grounds, 1998; Sadeh, 1988). In humans, complement activation remains at normal levels but neutrophil mobilization is significantly decreased in older subjects (Cannon et al., 1994). Age-associated deficits in macrophage activity have also been reported in a mouse model of cutaneous wound healing and faster wound healing was observed when young macrophages were applied to the wounds of old mice (Danon et al., 1989). Auto- and allograft muscle transplantation studies between SJL/J and BALB/c mice demonstrated that the superior regeneration capacity observed in SJL/J hosts correlated with their ability to recruit leukocytes faster than BALB/c hosts (Roberts et al., 1997). The impaired macrophage function observed in old SJL/J mice was eventually shown to be specific to males of this strain as female SJL/J and other four strains of mice did not show this phenotype (Grounds, 1987). Nevertheless, it is well established that the efficiency of the immune system deteriorates with age (Warren et al., 2008); and thus, a role for altered inflammatory cell function in deficient repair of old muscles cannot be ignored (Grounds, 1998). In fact, the immune response that is necessary for wound clearing overlaps with muscle regeneration, and the same cytokine, namely IL-4, positively regulates fusion of both macrophages and myoblasts in vitro and in vivo (Horsley et al., 2003).

Recent studies are shedding light on the role of local extrinsic factors and processes in the stem cell niche that are associated with alterations in myogenic capacity with age. It appears that these extrinsic factors present in the old environment have deleterious effects on early muscle regeneration events such as satellite cell activation and proliferation (Conboy et al., 2002; Conboy et al., 2003; Conboy et al., 2005). Old satellite cells have functional Notch receptors, but they fail to activate Notch signaling in response to injury due to a lack of concomitant, injury-stimulated Notch ligand Delta upregulation (Conboy et al., 2003; Wagers et al., 2005). Remarkably, muscle repair in old animals can be rejuvenated by forced Notch activation and, conversely, the regenerative processes of muscle in the young can be aged by inhibiting Notch signaling (Conboy et al., 2003; Wagers et al., 2005). Additionally, co-culture experiments of muscle fibers and young satellite cells or human embryonic stem cells (hESCs) showed that the regenerative potential and proliferative capacities of both stem cell types are significantly diminished when they are exposed to old local niches such as aged, dissociated myofibers (Carlson et al., 2007). Besides loss of Notch pathway activation with age, a recent study from our laboratory reveals that higher levels of TGF- β are present in aged satellite cell niches as compared to young (Carlson et al., 2008). Further analysis shows higher TGF- β pathway activation (i.e., elevated pSmad3) in old as compared to young satellite cells, and a physical competition between Notch and pSmad3 occurring at the promoters of multiple cyclin-dependent kinase (CDK) inhibitors (Carlson et al., 2008). In aged myofiber-associated niches, it is evident that the lack of Notch activation combined with TGF- β up-regulation lead to excessive pSmad3-mediated transcription of cell cycle inhibitors, which thus antagonize satellite cell proliferation and, at least in part, contribute to deficient muscle repair (Figure 1A).

Other components present in the satellite cell microenvironment, such as heparan sulfate proteoglycans, have been found essential in regulating satellite cell maintenance, activation, proliferation and differentiation during the muscle repair process (Cornelison et al., 2001; Langsdorf et al., 2007). Although to the best of our knowledge, no age-related alterations in these molecules have been established so far, it is worth noting that cellular infiltrates can induce syndecan expression in mammalian cells during the wound repair process (Gallo et al., 1994; Grounds, 1998) and thus the decreased inflammatory cell activity observed in old animals (Cannon et al., 1994; Danon et al., 1989; Grounds, 1998; Sadeh, 1988; Zacks et al., 1982) may affect the ability of muscle cells to express proteoglycans in these animals. On the other hand, twice as much endomysial collagen is found in 26-week-old as compared to 3-week-old wild-type and dystrophic mice (Marshall et al., 1989). Dystrophic animals in particular display not only an increased collagen content in both endomysium and perimysium (Marshall et al., 1989) but also an accumulation of atypical types of collagen (Alexakis et al., 2007; Grounds et al., 1993; Grounds, 1998; Marshall et al., 1989). In addition to collagen, the basal lamina surrounding satellite cells has also been reported to increase in aged muscle fibers (de Maruenda et al., 1978; Grounds, 1998; Snow, 1977). Another connective tissue-related change with age or disease includes alterations in the paracrine effect of fibroblast-derived growth factors on myoblast proliferation (Grounds, 1998; Quinn et al., 1990).

Besides local niche aging processes, age-related factors in the systemic niche also have to be considered in order to understand the mechanisms underlying skeletal muscle stem cell aging. Parabiotic pairing experiments, wherein animals share a common circulatory system, between young and old mice demonstrated that the regeneration capacity of aged satellite cells (and liver progenitor cells) can be rejuvenated by exposure to a young systemic milieu, without any recruitment of young cells from the shared circulation (Conboy et al., 2005; Wagers et al., 2005). Both in vivo heterochronic parabiosis and in vitro exposure to sera from young animals can restore Notch activation in old satellite cells, which are then able to proliferate and repair muscle as well as young cells (Carlson et al., 2007; Conboy et al., 2005; Wagers et al., 2005). On the other hand, old sera or a mixture of young and old sera can rapidly age the regenerative responses of both young satellite cells and hESCs (Carlson et al., 2007). The negative effects of old and heterochronic systemic milieu as well as of old local organ niches, on both mouse myogenic progenitor cells and hESCs, suggest that the extrinsic mechanisms of the age-associated regulation of stem cell responses are evolutionarily conserved across mammalian species and stem cell categories (Carlson et al., 2007). Furthermore, the same study demonstrated that hESCs secreted as of yet unidentified factors that significantly improved the myogenic potential of primary myoblasts in vitro as well as of young and old satellite cells both in vitro and in vivo (Carlson et al., 2007). Undoubtedly, the identification of the age-specific factors in young and old systemic niche environments, and the rejuvenating factors produced by hESCs, will reveal novel therapeutic avenues for regenerative medicine using cellular-, stem cell- and drug-based approaches.

Notably, since young satellite cells and hESCs were negatively affected when exposed to the old or heterochronic systemic milieu (Carlson et al., 2007), it can be inferred that it is not simply a lack of “positive” myogenic factors in the old circulation, but rather the presence of inhibitory factors in the aged systemic niche, that lead to a reduction in productive tissue repair. It would be interesting to investigate whether abnormal levels of soluble secreted molecules, such as TGF- β , that are characteristic of aged tissues (Carlson et al., 2008) lead to their systemic elevation in aged animals. In fact, old humans and rats have reduced serum levels of growth hormone and insulin-like growth factor-I (IGF-I) (Grounds, 1998). Alterations in the levels of such systemic factors may influence satellite cell behavior directly or indirectly via modulations of the immune system given that inflammatory cell activity is relevant to muscle regeneration, at least partially (Grounds, 1998).

Another potential age-specific candidate in the extrinsic systemic milieu of aged animals is the Wnt family of proteins. The decline in satellite cell regeneration capacity observed with age is also accompanied by increased tissue fibrosis (Alexakis et al., 2007; Grounds, 1998; Marshall et al., 1989), which appears to be associated with a myogenic-to-fibrogenic cell fate conversion of muscle stem cells, most likely via factors in the aged systemic environment that can bind to the Frizzled protein family (Brack et al., 2007). Accordingly, this lineage fate conversion appears to be driven by the activation of the canonical Wnt pathway in aged satellite cells as addition of exogenous Wnt or Wnt inhibitors can age the response of young satellite cells or rejuvenate old satellite cells, respectively, both in vitro and in vivo (Brack et al., 2007). In the mouse model of Duchenne muscular dystrophy, old mdx myoblasts seem to be reprogrammed to a profibrotic activity whereby collagen type I deposition impairs productive muscle regeneration and causes even more collagen synthesis, thus creating a major deleterious positive feedback mechanism (Alexakis et al., 2007). It is therefore also possible that Wnt signaling plays a role in the context of muscle degeneration associated with muscular dystrophies.

The location of satellite cells on the skeletal muscle fiber niche as well as the processes involved in the aging of satellite cell regenerative responses are schematically represented in Figure 2A.

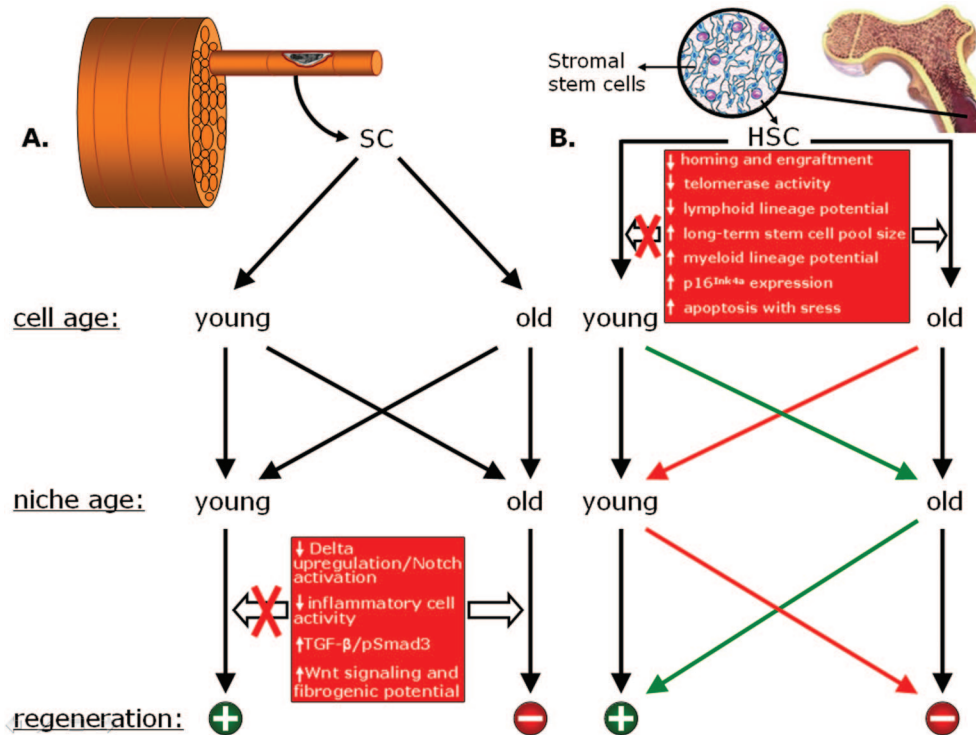


Figure 2. Extrinsic versus intrinsic aging mechanisms in satellite cells and hematopoietic stem cells. Schematic depictions of satellite cell (SC) and hematopoietic stem cell (HSC) locations in the muscle fiber and bone marrow, respectively, and observed regenerative outcomes with respect to the age of the stem cell and its microenvironment or niche. **A.** Young or old SCs, when placed in contact with old systemic or local niches, both in vitro and in vivo, fail to generate productive tissue repair. Conversely, when SCs from young or old animals are immersed in a young microenvironment, both in vitro and in vivo, they regenerate muscle tissue appropriately. Thus the age of the extrinsic environment most likely determines the regenerative potential of SCs. The potential effects of the aged niche on SC responses are summarized in the red box. **B.** HSCs from young animals, when transplanted into either young or old hosts, produce successful regenerative responses while aged HSCs fail to regenerate properly regardless of the age of the host. Colored arrows indicate the procedure and proper outcomes of heterochronic HSC transplantations. Therefore it appears that, unlike SCs, HSC aging is probably regulated by intrinsic mechanisms that are unaffected by the age of the host environment. These prospective intrinsic aging mechanisms in HSCs are summarized in the red box.

In contrast to the case in satellite cells, mainly intrinsic factors appear to regulate the aging process of HSCs, which are the best characterized organ stem cells. Interestingly, the state of quiescence is not a unique feature of satellite cells, but is also typical of the least differentiated, long term hematopoietic stem cells (LT-HSCs) that have the highest capacity for self renewal. Furthermore, there is a larger body of knowledge on how quiescence is established and maintained in HSCs than in satellite cells. CD34⁻ c-Kit⁺ Sca-1⁺ lineage marker-negative (Lin⁻) (CD34⁻ KSL) HSCs represent only 0.004% of all mouse bone marrow mononuclear cells and about 40% of the CD34⁻ KSL population exhibit long-term repopulation capacity (Yamazaki et al., 2006). The majority of this cell population (about 94%) does not incorporate Pylonin Y and does not express the Ki-67 proliferation marker, which indicates that most mouse LT-HSCs are in the G0 phase of the cell cycle (Yamazaki et al., 2006). Moreover, HSC entry into the quiescent state seems to be regulated by the PI3K–Akt–FOXO pathway via inhibition of lipid raft clustering (Yamazaki et al., 2006). However, the quiescent HSC state is associated with a reduction in checkpoint control and DNA damage responses in the context of repair or apoptosis, which leads to accumulation of genomic damage in these cells with age (Rossi et al., 2007). Indeed, microarray expression analysis showed that genes associated with genomic stability and chromatin remodeling were downregulated in old HSCs (Chambers et al., 2007). Thus it is possible that old HSCs fail to respond properly under stress or tissue repair conditions due to this age-related accrual of DNA damage (Rossi et al., 2007).

It was initially reported that the Thy-1^{lo} Sca-1^{hi} Lin⁻ Mac-1⁻ CD4⁻ c-Kit⁺ LT-HSC population from mouse bone marrow both accumulated with age and entered the cell cycle more frequently in old animals (Morrison et al., 1996). However, later studies using the CD34⁻ KSL LT-HSC population have demonstrated that the percentage of cells in the quiescent state does not vary significantly with age (Chambers et al., 2007; Rossi et al., 2007; Sudo et al., 2000).

Nonetheless, there is a marked accumulation of the HSC pool with age, most likely as a result of symmetric divisions (Sudo et al., 2000), but the presence of these extra HSCs is not beneficial since they present deficits in functional activity (Chambers et al., 2007; Sudo et al., 2000). These defective LT-HSCs are most likely the result of the increased DNA damage with age associated with the HSC quiescent state (Rossi et al., 2007). Additionally, the decline in expression of chromatin regulators and the subsequent epigenetic dysregulation observed in HSCs may actually be caused by environmental influences and lead to secondary aging effects, including higher cancer rates (Chambers et al., 2007). The nature of the age-associated defects present in HSCs will be discussed in more detail below.

Although most adult human cells have no detectable levels of telomerase, HSCs express low to moderate telomerase activity levels (Allsopp et al., 2002). Intriguingly, this readily detectable telomerase activity in the hematopoietic system is unable to prevent telomere shortening in lymphocytes *in vitro* and in aging peripheral blood leukocytes *in vivo* (Allsopp et al., 2002). Moreover, HSCs possess a finite replicative potential as they can be serially transplanted 5 to 7 times in mice, and their telomeres do shorten throughout the replicative aging process (Allsopp et al., 2002). Thus, one plausible hypothesis for the presence of telomerase in HSCs is to counter, at least partially, the deleterious effects of accelerated telomere shortening in HSC-derived hematopoietic lineages (Allsopp et al., 2002). Another possibility is that telomerase is only transiently activated in those particular hematopoietic cells that possess long-term replicative demands, to allow expansion of their replicative lifespan (Allsopp et al., 2002).

HSCs overexpressing telomerase may be serially transplanted no more than four times (close to wild-type HSCs) and in telomerase-deficient HSCs this number falls to only two times due to accelerated telomere shortening. This suggests that telomerase is required to avoid premature loss of telomeres, but other telomere-independent mechanisms are at work in regulating HSC regenerative potential (Park et al., 2004). Bmi1, a polycomb group member which is expressed at high levels in both HSCs and neural stem cells, may be part of these telomere-independent mechanisms as it was shown to regulate self-renewal and pool size of HSCs and most likely multiple types of somatic stem cells (Park et al., 2004). Bmi1 regulates HSC self-renewal by modulating key genes involved in stem cell fate decisions, survival and antiproliferation, including Ink4a locus genes (p16^{Ink4a} and p19^{Arf}), telomerase, and apoptosis inhibitor-6 (Park et al., 2004). These genes are associated with cell-cycle checkpoint programs that may contribute to organism aging and stem cell exhaustion via induced senescence or apoptosis (Janzen et al., 2006; Krishnamurthy et al., 2006; Molofsky et al., 2006; Orford et al., 2008; Park et al., 2004; Pelicci, 2004).

Although it has not been determined so far if Bmi1 expression is altered during stem cell transplantations and/or aging, at least one of its downstream targets, p16^{Ink4a}, which is an important regulator of cellular senescence, appears to accumulate in aged or stressed HSCs (Janzen et al., 2006; Orford et al., 2008; Park et al., 2004). Old mouse HSCs have impaired repopulating, homing and survival capabilities as compared to young, but old p16^{-/-} HSCs perform as efficiently as young wild-type HSCs in serial transplantation assays (Janzen et al., 2006; Orford et al., 2008). Similarly, reports on mouse forebrain and pancreatic islets reveal that increased p16^{Ink4a} expression also affected the regenerative capacity of these organs with age, and that p16-deficient animals were partially rescued from these negative age-associated phenotypes, and responded better to stress (Krishnamurthy et al., 2006; Molofsky et al., 2006).

Aged bone marrow has a decreased hematopoietic compartment, which is replaced by adipose tissue deposits, which are reminiscent of the replacement of functional muscle by fatty-fibrous tissue in the old (Gruver et al., 2007). Age-specific alterations in the cytokine milieu produced by and affecting the bone marrow are implicated in its morphological and stem cell output changes observed in the old, which is generally similar to the aging of muscle (Gruver et al., 2007). Examples of alterations in the cytokine and hormone networks with age include decreased systemic growth hormone, which can rescue proper cellularity and lower adiposity in the bone marrow of aged mice, diminished secretion of TNF by bone marrow-resident macrophages, and also bone marrow stromal cells themselves lower their levels of IL-7 secretion (Gruver et al., 2007). However, there is still no critical evidence that HSC numbers decline with age in the compromised hematopoietic compartment within the bone marrow (Gruver et al., 2007). In fact, as mentioned above, overall HSC numbers appear to increase in aged mice, and this effect is most likely intrinsic to LT-HSCs as evidenced in transplantation experiments from old to young animals (Park et al., 2004; Rossi et al., 2007). Nonetheless, it is known that many more old HSCs are necessary to completely reconstitute an ablated immune system, probably due to deficits in numerous HSC functions, including the lack of commitment to the lymphoid lineages (Gruver et al., 2007; Janzen et al., 2006; Rossi et al., 2007).

Unlike the case of skeletal muscle satellite cells, the age of the HSC niche seems of little relevance in regulating HSC behavior. When purified LT-HSCs from young and old mice were transplanted into young hosts, the total contribution from aged HSCs to B-, T- and myeloid cell lineage reconstitution was consistently lower than in mice receiving young HSCs (Rossi et al., 2005; Rossi et al., 2007). Additionally, this old LT-HSC-derived population had

decreased peripheral B-lymphocyte numbers, but an increased proportion of myeloid cells (Rossi et al., 2005; Rossi et al., 2007). Conversely, transplantation of young purified LT-HSCs into young and old animals revealed that even in the aged bone marrow microenvironment, young HSCs produced B-cells at proper levels and thus scarce B-lymphopoiesis seems to be intrinsic to HSC aging and not due to the aging bone marrow microenvironment (Rossi et al., 2005; Rossi et al., 2007). Interestingly, aged mice possess lower levels of common lymphoid progenitors, thus substantiating the notion that the age-specific features observed in HSCs are transplantable and cell autonomous (Rossi et al., 2005; Rossi et al., 2007). The intrinsic properties inherent in HSC aging were further corroborated by comparing young and old purified LT-HSCs using whole genome microarray analysis, which demonstrated that lymphoid and myeloid specification genes were downregulated and upregulated, respectively, in aged animals (Rossi et al., 2005; Rossi et al., 2007).

Therefore, the emergence of age-related immune dysfunctions and myeloid leukemias are thought to be caused by abnormalities in the HSC developmental potential as these cells predominantly differentiate into myeloid lineages at the expense of lymphoid lineages in aged animals (Orford et al., 2008; Rossi et al., 2005; Rossi et al., 2007; Signer et al., 2007). This age-related myeloid leukemia is not associated with increased HSC cycling since the percentage of LT-HSCs in the G0 phase remains practically the same as animals age (Chambers et al., 2007; Rossi et al., 2007; Sudo et al., 2000). In fact, data from a mouse model of chronic myeloid leukemia (CML) wherein HSCs are transformed by the BCR-ABL^{P210} oncogene in adulthood shows that transformed bone marrow cells from young animals displayed both a myeloproliferative disorder (MPD) and B-lymphoid leukemia, whereas transformed old bone marrow cells represented a better mimicry of the disease phenotype found in humans since these old HSCs induced MPD with rare lymphoid contributions (Signer et al., 2007). Thus the observed predominance of CML as adult-onset leukemia can potentially be explained by intrinsic age-specific defects that accrue in B-lineage cells and thus impair lymphopoiesis (Signer et al., 2007). Similarly, the extremely low incidence of human T-cell leukemia present in the elderly may be explained by the age-associated decrease in T cell production (Min et al., 2005; Signer et al., 2007).

The location of the HSC niche in the bone marrow and the key mechanisms associated with their aging process are summarized in Figure 2B.

However, it is important to keep in mind that the bone marrow niche may not be physiological during transplantation procedures since this experimental approach requires lethal doses of irradiation, genetic alterations, or treatment with anti-c-Kit antibodies (Czechowicz et al., 2007; Janzen et al., 2006; Leung et al., 2007; Opferman et al., 2005; Park et al., 2004). Moreover, the observation from serial-transplantation experiments that the capacity of HSCs to replenish the ablated bone marrow of mice is finite may stem from the activation of non-physiological stress responses due to the transplantation procedure itself as well as the excessive proliferative demands and clonal selection pressure imposed on these cells (Park et al., 2004).

In summary, a variety of interactive signaling networks become altered in organ stem cells and in their differentiated niches during the aging process. Neither the satellite cell pool nor the HSC reserve pools decline with age, but their functional properties do deteriorate in the old. In contrast to HSCs, muscle stem cells are intrinsically capable of life-long maintenance and repair of skeletal muscle, but the functional ability of these stem cells to proliferate in response to tissue injury or attrition is severely affected by the aging of their local niches, i.e. differentiated myofibers and ECM. Remarkably, the behavior of old muscle stem cells can be rejuvenated in “young” environments. The mechanisms associated with the aging of both satellite cells and HSCs, as well as the observed results of iso- and heterochronic experiments for both types of stem cells, are summarized in Figure 2.

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